

POTENTIAL IMPACTS OF CLIMATE CHANGE ON CALIFORNIA HYDROLOGY¹

Norman L. Miller, Kathy E. Bashford, and Eric Strem²

ABSTRACT: Previous reports based on climate change scenarios have suggested that California will be subjected to increased wintertime and decreased summertime streamflow. Due to the uncertainty of projections in future climate, a new range of potential climatological future temperature shifts and precipitation ratios is applied to the Sacramento Soil Moisture Accounting Model and Anderson Snow Model in order to determine hydrologic sensitivities. Two general circulation models (GCMs) were used in this analysis: one that is warm and wet (HadCM2 run 1) and one that is cool and dry (PCM run B06.06), relative to the GCM projections for California that were part of the Third Assessment Report of the Intergovernmental Panel on Climate Change. A set of specified incremental temperature shifts from 1.5°C to 5.0°C and precipitation ratios from 0.70 to 1.30 were also used as input to the snow and soil moisture accounting models, providing for additional scenarios (e.g., warm/dry, cool/wet). Hydrologic calculations were performed for a set of California river basins that extend from the coastal mountains and Sierra Nevada northern region to the southern Sierra Nevada region; these were applied to a water allocation analysis in a companion paper. Results indicate that for all snow-producing cases, a larger proportion of the streamflow volume will occur earlier in the year. The amount and timing is dependent on the characteristics of each basin, particularly the elevation. Increased temperatures lead to a higher freezing line, therefore less snow accumulation and increased melting below the freezing height. The hydrologic response varies for each scenario, and the resulting solution set provides bounds to the range of possible change in streamflow, snowmelt, snow water equivalent, and the change in the magnitude of annual high flows. An important result that appears for all snowmelt driven runoff basins, is that late winter snow accumulation decreases by 50 percent toward the end of this century.

(KEY TERMS: climate change; hydrologic impacts; streamflow; California.)

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INTRODUCTION

The Intergovernmental Panel on Climate Change Third Assessment Report (IPCC, 2001) and the U.S. Global Climate Change Research Program Report of the Water Sector (USGCRP, 2000) summarize potential consequences due to global warming. The IPCC reports that climate model projections with a transient 1 percent annual increase in greenhouse gas emissions show an increase in the global mean near-surface air temperature of 1.4 to 5.8°C, with a 95 percent probability interval of 1.7 to 4.9°C by 2100 (Wigley and Raper, 2001). Both reports indicate that likely changes during the 21st century include: higher maximum and minimum temperatures with a decreasing diurnal range over U.S. land areas, more intense precipitation events, increased summer continental drying, and increased risk of floods and droughts. To assess the impacts on water resources, hydrologic simulations are needed that are based on climate model projections and specified incremental temperature and precipitation changes that bracket the range of possible outcomes.

A number of investigations of California hydrologic response have focused on changes in streamflow volumes or timing due to climate change (e.g., Revelle and Waggoner, 1983; Gleick, 1987; Lettenmaier and Gan, 1990; Jeton *et al.*, 1996; Miller *et al.*, 1999; Wilby and Dettinger, 2000; Knowles and Cayan, 2002). Revelle and Waggoner (1983) developed regression models from historical data to estimate the sensitivity of streamflow in major basins to climate change. Gleick (1987) used a modified version of a spatially lumped

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water budget model (Thornthwaite and Mather, 1948) to represent the Sacramento drainage partitioned into upper and lower subbasins. Spatially uniform precipitation and temperature data from three GCMs and from sets of specified temperature and precipitation changes were then used as uniform input forcing to this model of the Sacramento River. Lettenmaier and Gan (1990) used precipitation and temperature from three GCM scenarios to force process based basin scale water budget models (Anderson, 1973; Burnash *et al.*, 1973) with three to five elevation band defined subbasins at four basins (North Fork American, Merced, McCloud, Thomas Creek) in the Sacramento/San Joaquin drainage. The Gleick and Lettenmaier and Gan studies did not downscale the GCM data before applying it as input to the basin-scale hydrologic models. Jeton *et al.* (1996) ran a distributed parameter precipitation runoff model (Leavesley *et al.*, 1983) to evaluate the North Fork American and East Fork Carson Rivers using specified incremental temperature and precipitation as uniform climate change scenarios. Miller *et al.* (1999) dynamically downscaled a GCM projection via a regional climate model and used the output as forcing to process based hydrologic models (Beven and Kirby, 1979; Leavesley *et al.*, 1983) in the North Fork American River and the northern coastal Russian River. Knowles and Cayan (2002) used historical precipitation and a single GCM projection of temperature that was statistically interpolated to a 4 km resolution as input forcing to a modified version of the Burnash *et al.* (1973) soil moisture accounting model for several watersheds in the Sacramento/San Joaquin drainage.

In general, these studies have suggested that Sierra Nevada snowmelt driven streamflows are likely to peak earlier in the season under global warming due to increased atmospheric greenhouse gas (GHG) concentrations. A key finding of these studies is that one of the greatest influences on streamflow sensitivity to climate change is the basin elevation relative to the freezing line location during snow accumulation and melt periods. To further understand the likelihood of potential shifts in the timing and magnitude of California streamflow and related hydrologic response, the following study analyzes six major basins forced by two GCM projections, statistically downscaled to 10 km, and representing the relatively warm/wet and cool/dry scenarios for California. An additional set of specified incremental temperature (shifts) and precipitation (ratios) changes were included to fully bracket the possibility of changes, and these range from a 1.5 to 5.0°C temperature increase and a +30 percent change in precipitation. This is the hydrologic component of a California Energy Commission study of climate change impacts on California (Wilson *et al.*,

2003). The decision to limit this study to two GCM scenarios was based upon the recommendations of the California Climate Change Panel (T. M. L. Wigley, personal communication), budget constraints, and demands on the other research components.

APPROACH

The focus of this study is to determine the range of hydrologic effects of projected climate change scenarios and to provide input for an assessment of California water resources. Streamflow sensitivities of the basins studied were related to a larger set of basins representing the entire Sacramento/San Joaquin drainage and have been applied to water demand and allocation simulations (Brekke *et al.*, 2002; J. R. Lund, personal communication, 2002).

Streamflow simulations in this study are based on the application of the National Weather Service River Forecast System (NWSRFS) Sacramento Soil Moisture Accounting (SAC-SMA) Model (Burnash *et al.*, 1973) coupled to the snow accumulation and ablation Anderson Snow Model (Anderson, 1973). The SAC-SMA has two upper zone storage compartments (free and tension) and three lower zone storage compartments (free primary, free secondary, and tension). The tension zone storage is depleted only by evapotranspiration processes, while the free zone water also drains out as interflow and baseflow. The SAC-SMA was chosen primarily due to its dependence on only two variables, precipitation and temperature, and because it is the operational model of the National Weather Service.

The Anderson Snow accumulation and ablation model within the NWSRFS directly computes the snow to rain elevation based on the input mean area temperature (MAT) and a lapse rate elevation adjustment. Using this computed freezing height, an area elevation curve is used to calculate the percentage of area receiving rain or snow. The area elevation curve and the elevation adjusted freezing line remove the need for a large number of elevation band subbasins for determining the percentages of snow and rain within each subbasin area.

The SAC-SMA with the Anderson Snow model has been used in previous climate change sensitivity studies (Lettenmaier and Gan, 1990; Nash and Gleick, 1991; Miller *et al.*, 2001) with an assumption of geomorphologic stream channel stationarity. Assuming fixed channel geometry requires that climate change simulations be based on perturbations about the historical data period for which the calibration was performed and verified. Historical temperature and

precipitation time series for 30 years (1963 to 1992) may be sufficiently long for a representative climatology and is available at six-hour time steps for each basin. Thirty-year periods are used to generate climatologies that conform to those used by the National Climate Data Center. Long term natural variability would be better accounted for if 100 years of data were available.

Six representative headwater basins with natural flow were selected for analysis: Smith River at Jed Smith State Park (SP), Sacramento River at Delta, Feather River at Oroville Dam, American River at North Fork Dam, Merced River at Pohono Bridge, and Kings River at Pine Flat Dam (Figure 1). The snow producing basins were delineated into upper and lower basins with separate input forcing to account for the elevation, land surface characteristics, and climate differences. Table 1 shows the basin size, location, percent area, and centroid of each upper and lower subbasin. The Smith is a very wet coastal basin where seasonal snowpack does not significantly accumulate. The Sacramento is a mountainous northern California basin with a small amount of seasonal snow accumulation. The Sacramento provides streamflow for the north and northwest drainage region into the Central Valley. The Feather and Kings represent the northernmost and southernmost Sierra Nevada basins for this study, respectively, and the Kings and Merced are the highest elevation basins. The American is a fairly low elevation Sierra Nevada basin but has frequently exceeded flood stage, which has resulted in substantial financial losses. This set of study basins provides sufficient information for a spatial estimate of the overall response of California's water supply (excluding the Colorado River), is distributed across the Sacramento/San Joaquin drainage, and was applied as input to a water allocation assessment study (Brekke *et al.*, 2002). This approach gives an indication of the potential range of impacts.

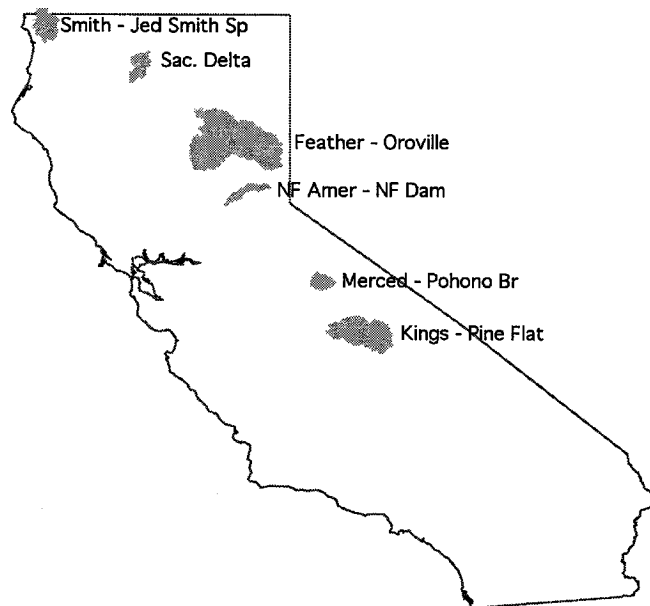


Figure 1. Location of the Six Study Basins (Smith at Jed Smith State Park, Sacramento at Delta, Feather at Oroville Dam, North Fork American at North Fork Dam, Merced at Pohono Bridge, and Kings at Pine Flat).

Hydrologic Model Verification

Daily streamflow verification was performed at the California Nevada River Forecast Center as part of the center's operational procedure. This verification is based on the historical National Weather Service (NWS) six-hour mean area precipitation (MAP) and mean area temperature (MAT) for each upper and lower basin and used as input to the SAC-SMA and SNOW17 hydrologic models. Historical daily streamflow was also provided by the NWS for the stream gages at the outlet of each of the six basins. The CNRFC calibrations and verifications used different sets of 10-year segments of the 1950 to 1993 six-hour precipitation and temperature and daily streamflow time series. Each basin has a model to observation

TABLE 1. Basin Area, Stream Gauge Coordinates, Percent Subbasin Area, and Elevation.

	Smith	Sacramento	Feather	American	Merced	Kings
Area (sq km)	1,706	1,181	9,989	950	891	4,292
Gage Latitude	41°47'30"	40°45'23"	39°32'00"	38°56'10"	37°49'55"	36°49'55"
Gage Longitude	124°04'30"	122°24'58"	121°31'00"	121°01'22"	119°19'25"	119°19'25"
Percent Upper	0	27	58	37	89	72
Upper Centroid Elevation (m)		1,798	1,768	1,896	2,591	2,743
Lower Centroid Elevation (m)	722	1,036	1,280	960	1,676	1,067

correlation of better than 90 percent for daily streamflow, as is required for operational use. Further details of NWS daily streamflow calibration procedures can be obtained through the CNRFC (Robert Hartman, personal correspondence).

This study used 30-year climatological verifications based on the 1963 to 1992 period and the CNRFC calibration parameters from above. Data for this 30-year period are the most complete that are available and are close to the National Climate Data Center's 1961 to 1990 climatology data for this region. Comparison of mean monthly observed to simulated climatological streamflow for 1963 to 1992 resulted in streamflow correlation coefficients greater than 0.95 for each of the six basins, which is well within the margin of error associated with GCMs.

Evapotranspiration as a Function of Temperature

The CNRFC version of the SAC-SMA has a set of fixed mean-monthly evapotranspiration (ET) demand curves representative of the calibration period. To generate future climate ET as a function of temperature, a set of ET ratios was introduced using the Hamon (1961) formula. This formula depends upon the near surface air temperature, latitude, and Julian day. It is adequate for such projected climate analyses where a relative ET sensitivity due to temperature is considered. Ratios of projected to historical ET were computed and used as multiplication adjustment factors for correcting ET with temperature change. Sensitivity studies were performed as part of this analysis and have shown that this is effective at capturing the changes in monthly ET with projected temperature. However, sensitivity studies of this adjustment have shown that it alters the streamflow results by less than five percent, which is smaller than the GCM errors. Hence this adjustment was not included.

Incremental Perturbations

Streamflow was forced by imposing incremental sets of constant temperature shifts ($T_{\text{shift,incr}}$) and precipitation ratios ($P_{\text{ratio,incr}}$) on the historical MAT and MAP time series. The selected incremental values represent the range of the mid and late 21st Century GCM projected changes. The specified temperature increases are 1.5°C, 3.0°C, and 5.0°C. The change in precipitation associated with future climate change is more uncertain than temperature, and consequently, decreases and increases were simulated (0.70, 0.82, 0.91, 1.00, 1.91, 1.18, and 1.30). Adjusted six-hour

temperature and precipitation input data were calculated by uniformly adding the temperature shift and by multiplying the precipitation ratio for each temperature and precipitation time series, $T_{\text{incr}}(t) = T(t)_{\text{hist}} + T_{\text{shift,incr}}$; $P_{\text{incr}}(t) = P(t)_{\text{hist}} * P_{\text{ratio,incr}}$. For each of the incremental changes, daily streamflow was simulated at each of the representative basins. From these daily streamflow outputs, monthly mean daily streamflow (CMSD) was computed for October 1963 to September 1992. Monthly climatological means were computed as the monthly mean daily streamflow for each month over this 30-year period.

Scenario Perturbations

As climate scenarios, the California Climate Change Panel selected a warm, wet GCM climate projection based on the Hadley Centre's HadCM2 run 1 and a cool, dry climate projection based on the NCAR PCM run B06.06, relative to the mean of the IPCC GCM projections for California. From these coupled atmosphere/ocean GCM simulations, two 30-year periods (2010 to 2039 and 2050 to 2079) and one 20-year period (2080 to 2099) were used. The GCM data were statistically downscaled and interpolated to a 10 km spatial resolution using historically derived regression equations based on the PRISM technique (Daly *et al.*, 1999). Monthly temperature shifts and precipitation ratios derived from the mean area basin climatologies were then imposed on the historical 1963 to 1992 temperature and precipitation time series as in the incremental studies. The California 10 km resolution temperature shifts averaged for each climatological period indicate that statewide, the PCM temperature difference increases to about 1.5°C by 2065 and to 2.4°C by 2090, while the HadCM increases to about 2.4°C by 2065 and to 3.3°C by 2090. The PCM precipitation ratios are reduced to about 0.91 of present precipitation by 2010 to 2039, 0.86 by 2050 to 2079, and 0.76 by 2080 to 2099, while the HadCM2 precipitation ratios increased significantly, to about 1.22 by 2010 to 2039, 1.32 by 2050 to 2079, and 1.62 by 2080 to 2099. Figure 2 shows these trends as California mean area projected temperature and precipitation using a 10-year running means.

Monthly mean area precipitation and temperature were determined for each upper and lower subbasin using the downscaled 10 km gridded temperature and precipitation based on the PCM and HadCM. Climatological monthly MAP and MAT values were calculated for the baseline 1963 to 1992 and for each projected period.

A ratio (shift) between the monthly basin MAP_{scen} (MAT_{scen}) climatologies for the projection time periods

and the monthly baseline historical precipitation (temperature) climatologies were computed. These climate scenario precipitation ratios ($P_{\text{ratio,scen}}$) and temperature shifts ($T_{\text{shift,scen}}$) were used to adjust the archived NWS observed time series in a similar manner as the constant incremental values, but in this case with monthly adjustments to represent seasonal variations in the projected climate change. The imposed climate scenario mean area precipitation and temperature time series were used as input to the hydrologic models as described in the incremental approach. The imposed temperature shifts and precipitation ratios are an approach that removes GCM bias and that was used in the IPCC Second and Third Assessment Reports.

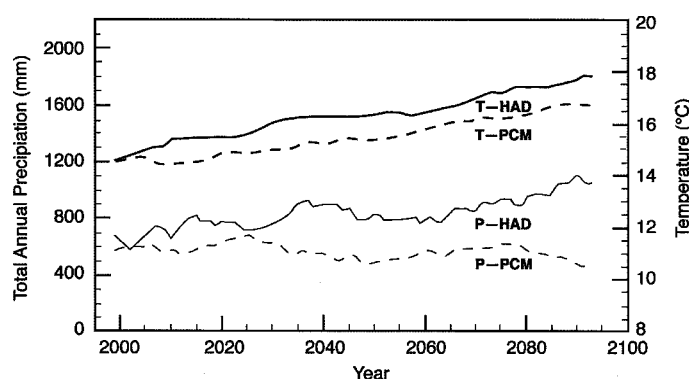


Figure 2. California Mean Area Temperature Shifts (°C) and Precipitation Ratios for PCM and HadCM2 for the Period 2000 to 2099.

RESULTS

Analysis of temperature and precipitation forcing and the resulting snow to rain ratio with elevation, snowmelt, and streamflow are based on the mean monthly climatologies. Shifts in the cumulative streamflow and exceedance probabilities are based on the daily 30-year time series and annual peak flow. By using daily values based on the historical data and the sensitivities that are imposed on the historical data, the streamflow simulations are sufficiently constrained during the calibration periods. This is a valid approach, as it relies on perturbations about the 1963 to 1992 CNRFC calibration periods. To keep the number of figures to a minimum, the Sacramento, American, and Merced Basins are graphically discussed, while the Smith, Feather, and Kings are only mentioned.

Temperature Forcing

Figure 3 shows the mean monthly temperature change at the headwaters of the Sacramento, American, and Merced Basins for the HadCM2 and PCM. The simulated temperature climatologies generally follow the historical seasonal trends, with near linear increases with projected time and increasing atmospheric carbon dioxide concentration. The greatest increases from the baseline are during the winter and summer seasons, with the largest increase during HadCM2 2080 to 2099, followed by HadCM2 2050 to 2079, then PCM 2080 to 2099. The monthly temperature shift ranges are 0.53°C to 4.70°C for the HadCM2 and -0.14°C to 3.00°C for the PCM.

Precipitation Forcing

The mean monthly precipitation for the same three headwater basins discussed above is shown in Figure 4. The warm, wet HadCM2 increases in monthly amounts during November to February and generally shifts the maximum precipitation by about one month earlier in the year. The PCM total annual precipitation is close to the historical precipitation; however, precipitation decreases during November to December and again during March and April for the 2050 to 2079 and 2080 to 2099 mean climates. In January, the 2050 to 2079 period shows a large increase, whereas the other months show a significant decrease.

The wet HadCM2 projection consistently shows higher precipitation ratios than the drier PCM projection. The HadCM2 has a minimum wet season precipitation ratio of 0.89 in December 2010 to 2039 and a maximum of 2.04 during February 2080 to 2099. The precipitation increase is relatively extreme compared to the mean of the IPCC GCM precipitation projections for California. The PCM precipitation ratios have a much smaller range, with a wet season minimum of 0.48 times the baseline in November 2080 to 2099 and a maximum of 1.16 times the baseline in January 2050 to 2079. In general, this PCM run dries down over the projected period and is in contrast to the HadCM2 precipitation projection. The 2080 to 2099 projected PCM precipitation shows a decrease in precipitation, while the HadCM2 exceeds the highest incremental ratio in the Merced and Kings Basins for 2050 to 2079 and in all basins for 2080 to 2099.

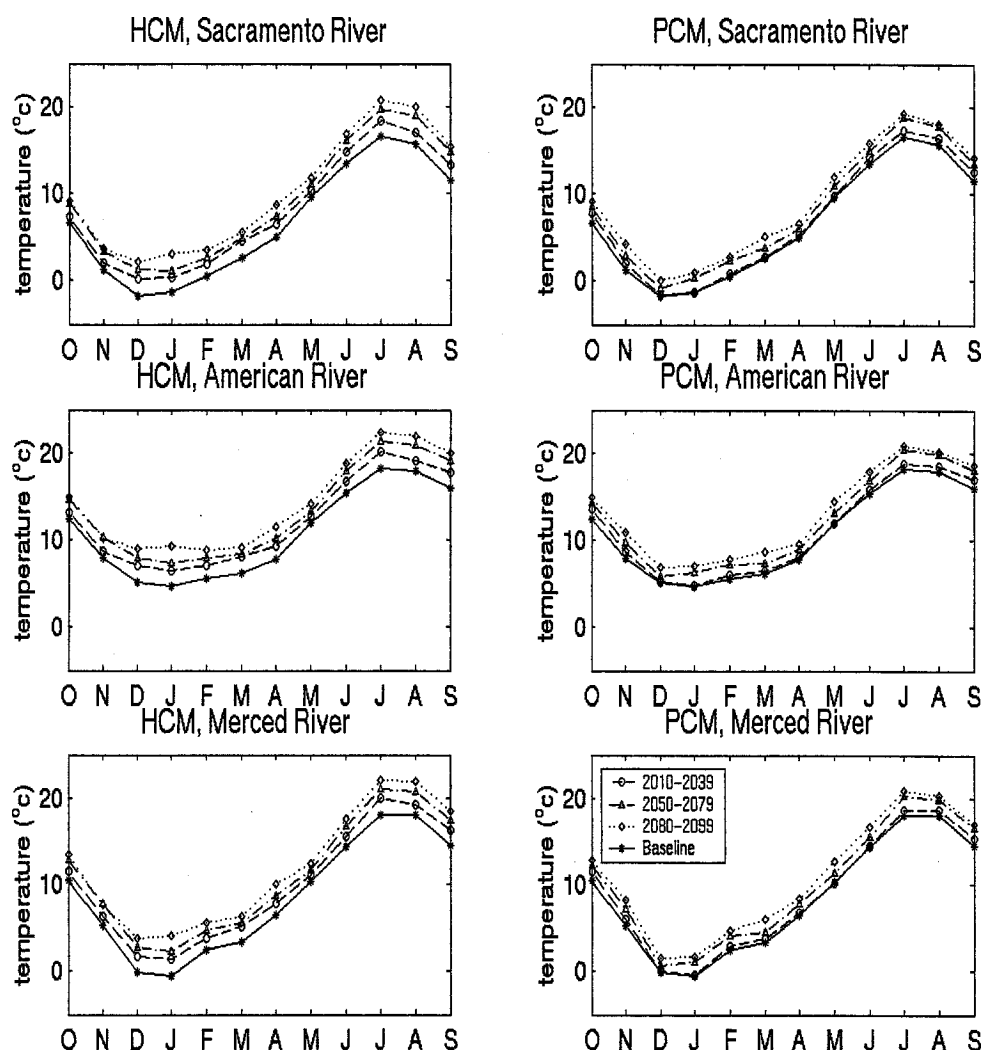


Figure 3. HadCM2 (HCM) and PCM Temperature Shifts Relative to the NWS Observed Temperatures at the Sacramento, American, and Merced Study Basins.

Streamflow Response

The streamflow response as forced by temperature and precipitation change is sensitive to the characteristics of the basin, particularly the snow line elevation and local weather patterns. Incrementally uniform temperature shifts (1.5°C, 3.0°C, and 5°C) are shown for decreasing, unchanged and increasing precipitation ratios (0.70, 0.82, 0.91, 1.00, 1.09, 1.18, and 1.30) in Figure 5.

For the basins studied, a 1.5°C increase is not sufficient for an earlier monthly peak flow. However, it is sufficient at 3°C for the American, Kings, and Feather and at 5°C for the other snow accumulating sub-basins. For all of the snow accumulating basins evaluated, the December to March monthly streamflow volume increases above the baseline and the May to August monthly streamflow decreases below the baseline. For the extreme 5°C temperature increase, the

mean monthly peak flow occurs one to two months earlier, except for the 70 percent precipitation on the Sacramento, which is not as snowmelt dominated as the other basins. The 3°C temperature increase shows similar but weaker shifts in timing and magnitude. Figure 6 shows the mean monthly streamflow for the Sacramento, American, and Merced, as forced by the relatively warm/wet and cool/dry scenarios. The warm and wet HadCM2 forced streamflow shows large increases in total annual streamflow, increases during the December to February (DJF) and March to May (MAM) seasons (for most of the basins) and earlier peak flow timing for the 2080 to 2099 period. The cool and dry PCM forced streamflow shows a modest increase in DJF flow volume for most of the snowmelt driven basins and decreased June to August (JJA) streamflow for all of the basins.

The runoff coefficient (streamflow divided by precipitation) increases during November to May and

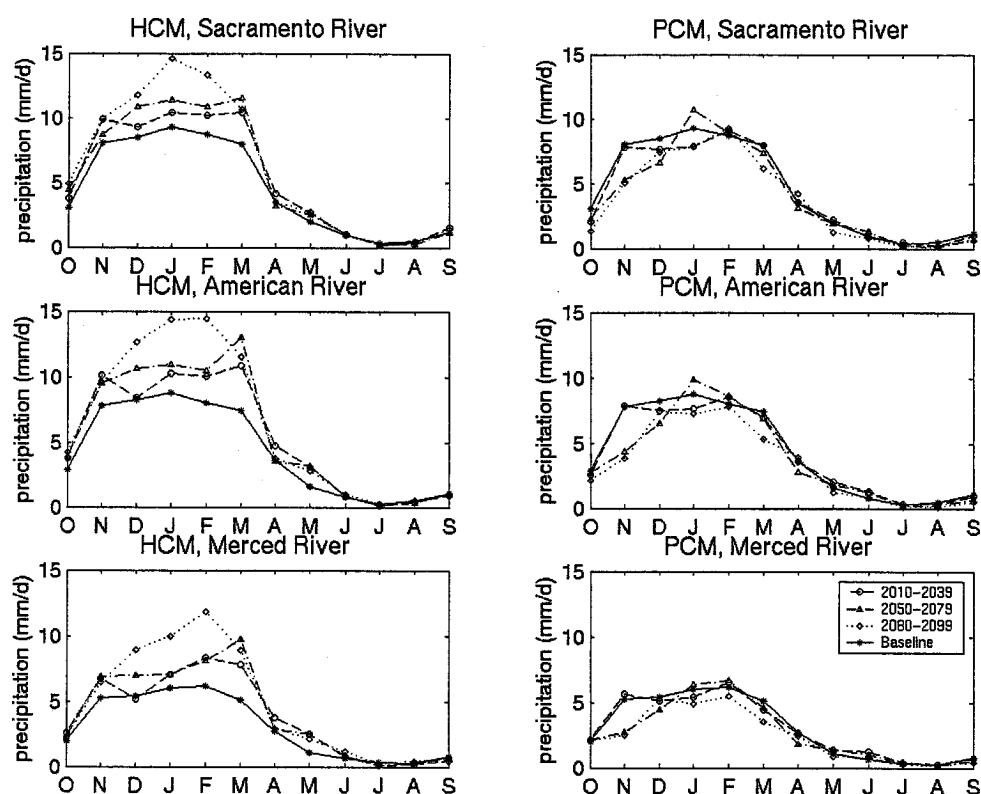


Figure 4. HadCM2 (HCM) and PCM Precipitation Ratios Relative to the NWS Observed Precipitation at the Sacramento, American, and Merced Study Basins.

decreases during April to July for the upper sub-basins as forced by both GCM scenarios. This is consistent with the increasing number of days above freezing for each subbasin. The timing changes are identified by the cumulative daily streamflow. For both the warm/wet and cool/dry simulations, the day in which 50 percent of the annual flow has occurred is earlier, as the projected streamflow goes from 2010 to 2100. The HadCM2 is very pronounced, with large shifts in both the amount and timing, while the PCM shows mainly a shift in timing and reduced magnitude. This is consistent with the PCM precipitation ratio decreasing. The HadCM2 streamflow shifts between 30 and 60 days earlier, and the PCM is less than or about 30 days earlier near 2100.

To understand the processes that bring about temperature dependent and precipitation dependent shifts in the streamflow magnitude and timing, an analysis of the climatological monthly snow to rain ratio, snow water equivalent, and snowmelt are presented.

Streamflow Response Uncertainty

The range of uncertainty based on these results is best described qualitatively. Large shifts based on the

sets of MAT and MAP values can be easily misinterpreted if numbers were to be provided. It is sufficient to state that monthly volumes can range from over a 100 percent increase to a 10 percent decrease in the winter and a spring/summer decrease of up to 20 percent.

Snow to Rain

The snow to rain ratios decrease with increasing temperature but vary significantly with latitude, location with respect to local weather patterns, and most importantly, the elevations of the lower and upper basins. In this study, the elevation band partition was based on the historical snow accumulation line. Hence, the lower subbasins typically have minimal to no accumulation, and the upper subbasins have the majority of the accumulated snow. High elevation subbasins (e.g., Upper Merced at 2,591 m) result in higher snow accumulation and later season runoff than the lower elevation subbasins (e.g., Upper Sacramento at 1,798 m). Although the HadCM2 projections show a significant increase in total precipitation and the PCM projections show reduced precipitation, both cases have a significant reduction of the snow to rain ratio due to warming.

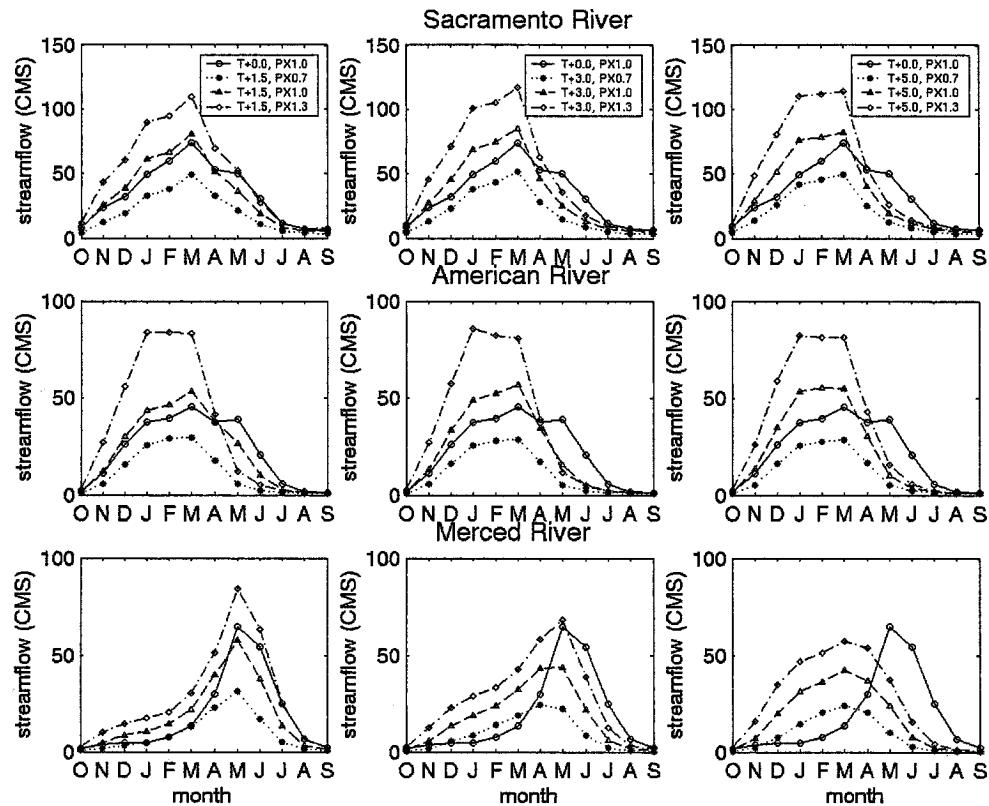


Figure 5. Streamflow Monthly Climatologies Based on the Specified Incremental Changes in Temperature Increase (1.5°C, 3°C, and 5°C) for Decreasing (0.70, 0.82, and 0.91) and Increasing Precipitation Ratios (1.09, 1.18, and 1.30).

Snow Water Equivalent

Snow Water Equivalent (SWE) is a measure of the snow depth and density and represents the liquid depth equivalent of the snowpack. Figure 7 shows the SWE climate change relative to the baseline SWE for Sacramento, American, and Merced Basins. The SWE decreases for most basins, except the very high Kings Basin (73 percent of the basin area is in the upper subbasin, which has a center of elevation at 2,743 m) under the wet and warm HadCM2 scenario. The large relative increase for the 2080 to 2099 climate during October and November is a ratio of small absolute values. For the PCM projections, the snow water equivalent is significantly reduced and the peak is earlier for all basins by 2080 to 2099. The critical factor is whether the historical temperature is sufficiently below freezing for the snowpack to be unaffected by a small temperature increase. In general, higher elevation basins are less sensitive and do not lose as much winter season snowpack as those with centroid elevations near the freezing line. In some high elevation basins at high latitude, there is an increase in total SWE, but the location is at higher elevations

than the historical location. The proportion of time (six-hour time steps) the upper subbasins are below freezing during January is given in Table 2. By 2090, the HadCM2 proportion of January that is below freezing decreases by more than 50 percent, while the PCM decreases by about 25 percent. However, the decreased precipitation in PCM results in a 50 percent decrease in SWE by April for the 2080 to 2099 time period, as does the HadCM2. This 50 percent reduction in both the warm/wet and cool/dry projections is significant, as April 1 is the time when the California Department of Water Resources determines water allocation and reservoir operation for the remainder of the year. This result is significant and aligned with other studies that evaluate projections that were not selected to reflect the envelope of possibilities.

Snowmelt

Snowmelt and rain represent the liquid water input for evaporation, infiltration, and streamflow response. The increased temperature and precipitation for the HadCM2 simulation yields a consistent

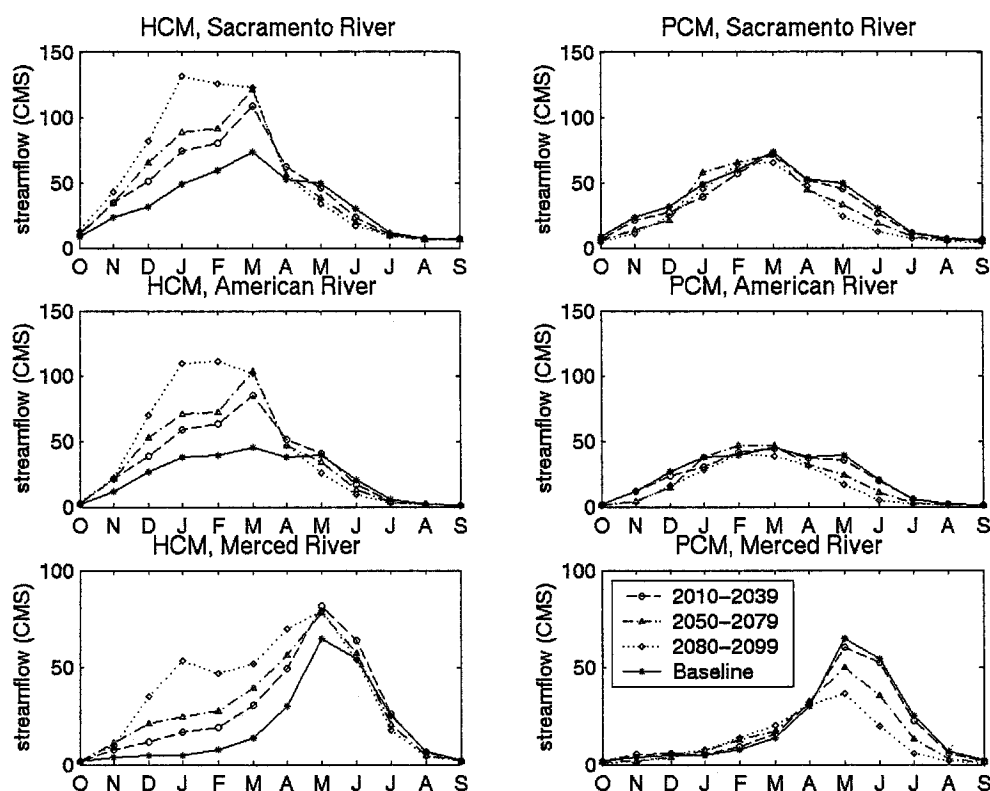


Figure 6. Streamflow Monthly Climatologies Based on the HadCM2 (HCM) and the PCM.

early season increase in liquid water as the projections go from 2010 to 2099 (Figure 8). Likewise, the relatively cool/dry PCM projection, with temperatures increasing at a slower rate, results in earlier snowmelt seasons at a slower rate. In general, the peak snowmelt month shifts earlier for low elevation basins that show significant decreases in snow water equivalent due to small increases in temperature. The sensitivity of snowmelt to the temperature increases depends on how many degrees the baseline temperature is below freezing while there is snow. The higher elevation basins that are less sensitive to small temperature increases do not respond with this degree of sensitivity due to the percent area well below freezing. In the high elevation upper Merced and Kings, the DJF temperatures are several degrees below freezing are less sensitive to small temperature increases than in the upper American, where the DJF temperatures are about 1°C below freezing. However, the change in snowmelt is more pronounced in lower-elevation basins during the early part of the century and then shifts to the higher elevation basins toward the end of the century. This reflects the proximity of the freezing line within the basins. An evaluation of the ratio of monthly climate change to baseline snowmelt (Figure 8) shows a large increase for the American and Merced during DJF and a large

decrease during May to July for the HadCM2. A similar but smaller shift occurs for the cooler and drier PCM.

Exceedance Probabilities

Changes in the snowmelt timing coupled with increased winter time warm precipitation (rain) suggest the increased likelihood of more extreme events such as floods. Ranking each set of 30-year peak annual daily flows and generating probability of exceedance plots (Figure 9) indicates that for the warm/wet HadCM2 there is a significant increase in the likelihood of high flow days and for the cool/dry PCM there is a slight increase. For each curve shown, the median of the annual maximum daily flow (50 percent) increases with increasing temperature. The 5 percent exceedance high flow for the projected climates exceeds current conditions, implying an increased likelihood of high flow days.

The change in high flows in response to both precipitation and temperature changes for the Smith River, Sacramento River, Feather River, and Merced River are represented in Figure 10. The mean maximum annual flow is shown for each combination of incremental temperature and precipitation changes

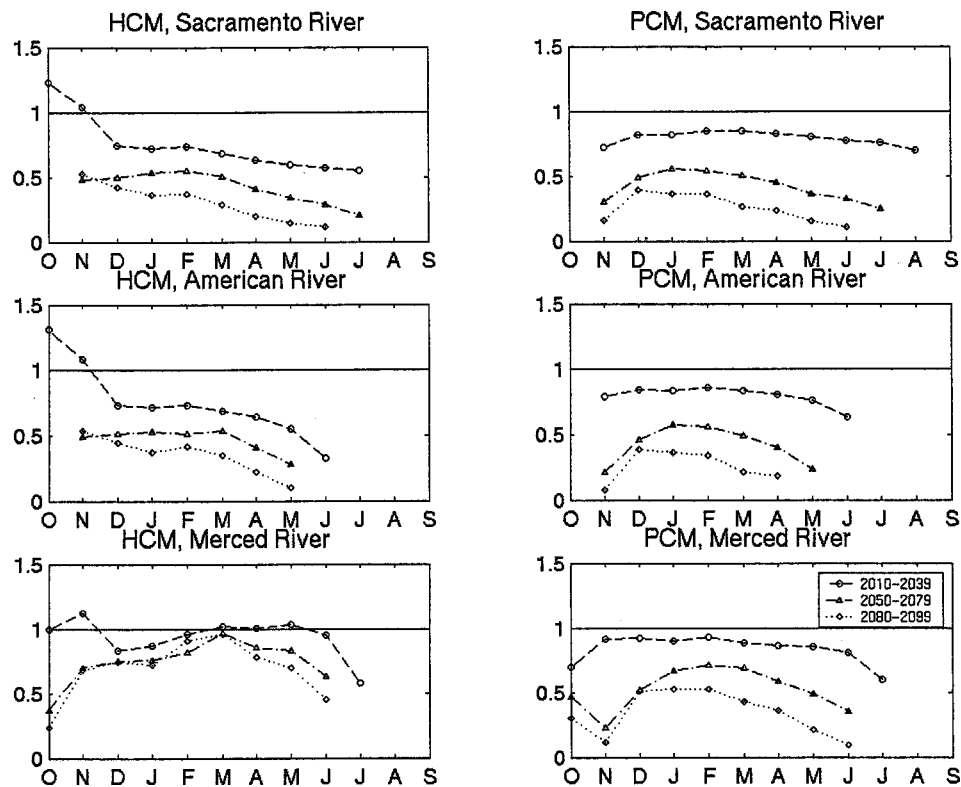


Figure 7. Ratio of Climate Change to Baseline Mean Monthly Snow Water Equivalent (SWE) for Each Basin.

TABLE 2. Proportion of January Six-Hour Timesteps Below Freezing for Each Upper Basin Where H Represents HadCM2 and P Represents PCM for Projected Climatological Periods 2025 (2010 to 2029), 2065 (2050 to 2079), and 2090 (2080 to 2099).

	Sacramento	Feather	American	Merced	Kings
Baseline	0.7140	0.6710	0.5634	0.6621	0.7002
H 2025	0.5538	0.5215	0.4368	0.5336	0.5619
P 2025	0.7228	0.6661	0.5556	0.6532	0.6895
H 2065	0.4941	0.4591	0.3782	0.4645	0.5014
P 2065	0.5624	0.5336	0.4470	0.5554	0.5901
H 2090	0.3153	0.3164	0.2478	0.3134	0.3546
P 2090	0.5005	0.4731	0.3989	0.5129	0.5449

relative to the historical baseline mean annual high flow. As might be expected, an increase in precipitation leads to an increase in high flows for each case. For each basin the proportional change in mean maximum annual flow is higher than the proportional change in precipitation. This suggests that high flow events for all basins studied are related to antecedent conditions, or storage in terms of soil moisture or snow.

The Smith River, which does not have snow accumulation, is insensitive to increasing temperature. However, a 30 percent increase in precipitation translates into a 50 percent increase in mean maximum

annual streamflow on the Smith. A similar increase in mean maximum annual streamflow for no temperature increase is seen for the Sacramento, Feather, and Merced. For all snow producing basins, mean annual high flows are sensitive to the degree of temperature change. With temperature increases of 1.5°C and 3°C, the mid-elevation Feather is most sensitive because the winter temperatures for a large percentage of the basin area are just below freezing under present conditions. A small increase leads to temperatures above freezing and therefore to less snow accumulation and earlier melting. This is seen in Figure 10 by comparing the relative change of the 1.5°C and

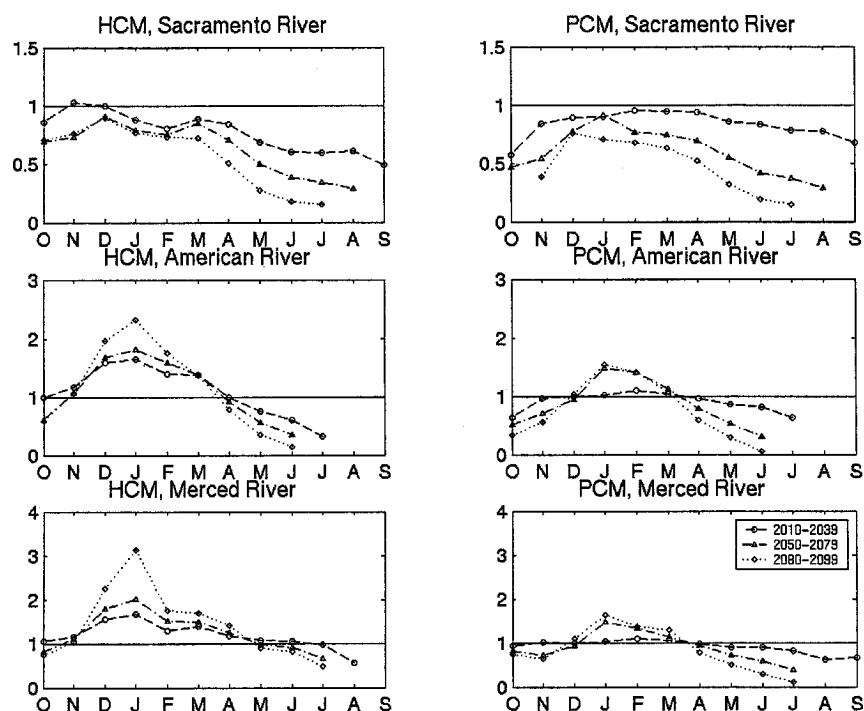


Figure 8. Ratio of Climate Change to Baseline Mean Monthly Snowmelt for Each Basin.

3.0°C mean annual high flows with changing precipitation for the Feather, Sacramento, and Merced. A larger temperature increase of 5°C does not lead to much higher flows in the Feather than that of 3°C; however, the Merced is very sensitive to temperature change within this range. Results suggest that with increasing temperature (1.5°C, 3.0°C, 5.0°C) the mean annual high flow will increase by approximately 30 percent, 60 percent, and 70 percent, respectively, for the Feather, 20 percent, 35 percent, and 40 percent for the Sacramento, and 25 percent, 50 percent, and 150 percent for the Merced. The Sacramento is less sensitive to temperature and more sensitive to precipitation than the other snow producing basins. The Sacramento is at a lower elevation than the other snow-producing basins, and therefore the high flows are probably more related to rainfall than snowmelt events.

WATER RESOURCES IMPACTS

In our companion paper (Brekke *et al.*, 2002), mean monthly streamflow changes were mapped onto 72 years of monthly historical streamflow for the California Valley Project State Water Project (CVP-SWP) reservoir inflows to evaluate the impacts on water

resources in California. Impacts downstream of the reservoirs were simulated using the California Water System Simulation Model (CALSIM) II 2001 Benchmark Study G-Model (BST2001), which was developed by the California Department of Water Resources in collaboration with the U.S. Bureau of Reclamation Mid-Pacific Region office (CALSIM, 2002). Results based on the relatively warm/wet HadCM2 suggest that the San Joaquin River Basin will experience substantial increases in reservoir inflow, moderate increases in stored water limited by existing capacity, increases in release volumes, and increases in agricultural deliveries. In contrast, results based on the relatively cool/dry PCM indicate delayed and significant decreases in reservoir inflow, stored water, and release volumes. The PCM results also suggest potentially severe impacts on agriculture may worsen due to water allocation policies that prioritize urban and environmental deliveries over agricultural.

SUMMARY

Determining the impacts of climate change on water resources by evaluating the response of the SAC-SMA to climate change scenarios and specified

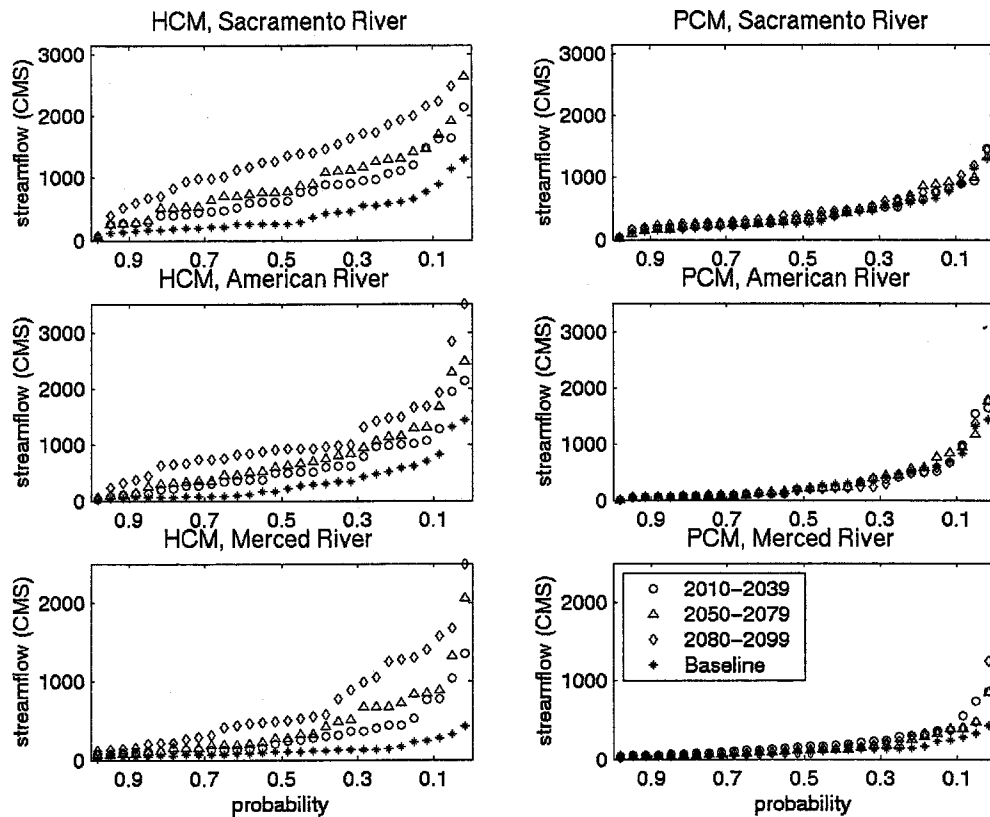


Figure 9. Exceedance Probabilities of the Peak Daily Flow for Each Year for Each Climate Change Scenario.

incremental changes is a valid approach. The temperature shifts and precipitation ratios imposed on the historical time series constrain the results to perturbations about the historical. This approach removes the variance in the climate change time series that indicate extreme events, intense precipitation events, and changes in diurnal temperature (IPCC TAR, 2001). However, this is one of the current impact assessment approaches used by the IPCC, and this study has been used for applications of water demand and agro-economic assessments.

Interpreting the results should remain somewhat qualitative and focus on trends, due to the overall uncertainty in model projections. The assumption of fixed land use results in surface characteristics in both the GCMs and the SAC-SMA that do not adequately represent future energy and water budgets. Using the SAC-SMA, Anderson Snow model, and a temperature dependent ET demand curve adequately portrays trends based on the sets of precipitation and temperature sensitivities.

The previous studies have shown similar results; however, this study provides an analysis based on the NWS operational model with detailed mean monthly shifts in variables (snowmelt, snow water equivalent, snow to rain) that directly indicate streamflow

response. The earlier studies were based on equilibrium climate change ($2 \times \text{CO}_2$) GCM simulations and did not include a transient 1 percent per year increase GHG and/or did not provide spatially downscaled input precipitation and temperature at the 10 km scale, as was used in this study. Nonetheless, the present findings are in agreement with the overall results of past studies, and the detailed analysis for multiple basins that indicate spatial dependence on local climate patterns, freezing height, and basin snow cover area are viewed as significant new findings.

Several aspects of simulated climate projection and impacts analysis should be extended. First, GCMs should continue to improve in accuracy with further studies to evaluate their results and reduce model bias. More GCM ensemble members should be generated to determine intermodel and intramodel variability. A multivariate weighting scheme based on the Atmospheric Model Intercomparison Project statistics can be constructed as a tool for separating well performing GCMs from those with significant deficiencies. Archived subdaily time series will reduce the amount of statistical interpolation, allow for analysis of higher moments (extreme events), and reduce errors.

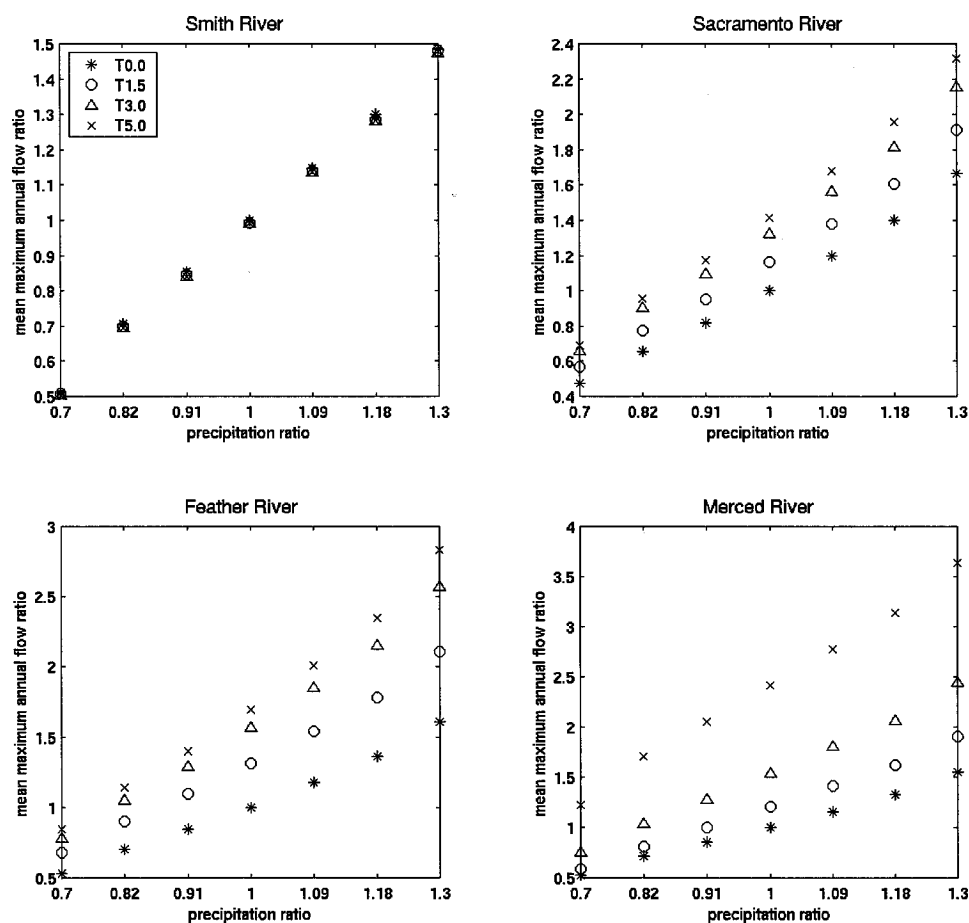


Figure 10. Ratio of Mean Annual High Flow for Changing Temperature and Precipitation to the Baseline Historical Mean Annual High Flow for All 28 Possible Incremental Combinations.

Second, dynamic downscaling should be incorporated into these studies. A key question is: what scale is required for capturing orographically produced precipitation in California? Statistical downscaling of GCM data will increase the resolution but will not capture orographic precipitation properly. Other important questions are: how many downscaled runs are required for quantifying regional climate model variability, and should there be an ensemble of downscaled simulations, each with slightly different initial conditions, for each GCM simulation?

Given the above limitations, this study does provide an important and reasonable set of upper and lower bounds of hydrologic response to climate change in California. Climate models will never predict the future but can provide projections with an uncertainty that can be bracketed. It is these bracketed solution sets that may ultimately provide water resources decision makers with the type of information needed to safeguard this most essential natural resource.

CONCLUSIONS

An analysis was performed of California hydrologic response due to temperature shifts and precipitation ratios based on two GCM projections and a range of specified uniform changes. Streamflow and snowmelt timing shifts are discussed as the set of possible outcomes. A comparison of the set of future climates to present day climates studied in this manuscript indicates that future projections have fewer freezing days, implying a decrease in snow accumulation. More water flows through the system in the winter, and less will be available during the dry season. An important result that appears for all snowmelt driven runoff basins is that late winter snow accumulation decreases by 50 percent toward the end of this century.

The above results suggest that the range of possible climate change responses is due to large scale change and local characteristics. This could be intensified if there are large scale frequency and/or intensity changes in natural low frequency variations (e.g.,

ENSO, PDO, AO). Large scale weather patterns that influence precipitation and runoff timing may dynamically shift, with significantly different local climates.

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